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# The Ramsey number of diamond-matchings and loose cycles in hypergraphs

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## Abstract

The 2-color Ramsey number  $R(\mathcal{C}_n^3, \mathcal{C}_n^3)$  of a 3-uniform loose cycle  $\mathcal{C}_n$  is asymptotic to  $5n/4$  as have been recently proved by Haxell, Łuczak, Peng, Rödl, Ruciński, Simonovits and Skokan. Here we extend their result to the  $r$ -uniform case by showing that the corresponding Ramsey number is asymptotic to  $\frac{(2r-1)n}{2r-2}$ . Partly as a tool, partly as a subject of its own, we also prove that for  $r \geq 2$ ,  $R(kD_r, kD_r) = k(2r-1) - 1$  and  $R(kD_r, kD_r, kD_r) = 2kr - 2$  where  $kD_r$  is the hypergraph having  $k$  disjoint copies of two  $r$ -element hyperedges intersecting in two vertices.

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# 1 Introduction

The  $r$ -uniform loose cycle  $\mathcal{C}_n^r$ , is the hypergraph with vertex set  $[n] = [m(r-1)]$  and with the set of  $m$  edges  $e_i = \{1, 2, \dots, r\} + i(r-1)$ ,  $i = 0, 1, \dots, m-1$  where we use  $\pmod n$  arithmetic. Notice that  $\mathcal{C}_n^r$  has  $n$  vertices and  $\frac{n}{r-1}$  edges and for  $r = 2$  we get the usual definition of a cycle in graphs. The Ramsey number  $R(\mathcal{C}_n^r, \mathcal{C}_n^r)$  is the smallest integer  $N$  for which there is a monochromatic  $\mathcal{C}_n^r$  in every 2-coloring of the edges of the complete  $r$ -uniform hypergraph  $K_n^r$ . It was proved in [16] that  $R(\mathcal{C}_n^3, \mathcal{C}_n^3)$  is asymptotic to  $5n/4$ . In this paper we extend that result by showing that for  $r \geq 3$ ,  $R(\mathcal{C}_n^r, \mathcal{C}_n^r)$  is asymptotic to  $\frac{(2r-1)n}{2r-2}$ . In the proof we follow the argument of [16]. It uses an important tool established by Łuczak in [19] that have been successfully applied in recent results [7], [12], [13], [14], [15]. Vaguely, the method reduces the problem of finding the Ramsey number of a path or a cycle to finding the Ramsey number of a connected matching. An additional - usually technical - difficulty is that the coloring is not on the edges of a complete hypergraph but on an almost complete one, where  $\epsilon \binom{n}{r}$  edges may be missing.

The key element in [16] was to search for a monochromatic connected structure with many diamonds, where the diamond  $D_3$  is two triples intersecting in two vertices. More precisely, it was proved that in any 2-coloring of the edges of an almost complete 3-uniform hypergraph with  $n$  vertices, there is a color, say red, such that there are vertex disjoint red diamonds covering approximately  $\frac{4n}{5}$  vertices and all of them are in the same component of the hypergraph determined by the red edges. In this paper we extend this result for the  $r$ -uniform diamond  $D_r$ , defined as two  $r$ -element edges intersecting in two vertices. (In fact, one may consider also  $D_2$  as an edge of a graph.) The two vertices are called the *central vertices* of the diamond. A *diamond matching* is the union of vertex disjoint diamonds. A diamond matching is *connected* if all of its vertices are in the same component of the hypergraph.

Our main result is the following.

**Theorem 1.** *Suppose that  $r$  is fixed and the edges of an almost complete  $r$ -uniform hypergraph  $\mathcal{H}$  with  $n$  vertices are 2-colored. Then there is a monochromatic connected diamond matching  $kD_r$  such that  $|V(kD_r)| \sim \frac{(2r-2)n}{2r-1}$ .*

The method of [16] can be used to derive from Theorem 1 the following.

**Theorem 2.**  $R(\mathcal{C}_n^r, \mathcal{C}_n^r) \sim \frac{(2r-1)n}{2r-2}$ .

Partly as a tool, partly as a subject interesting in its own, we determine exactly the 2- and 3-color Ramsey numbers of a diamond-matching:  $R(kD_r, kD_r) = k(2r-1) - 1$  (Theorem 4),  $R(kD_r, kD_r, kD_r) = 2kr - 2$  (Theorem 5).

## 1.1 Ramsey numbers for multiple copies

If  $H_0$  is a fixed  $r$ -uniform hypergraph, a multiple copy of  $H_0$  is meant to be a hypergraph  $H = kH_0$ , the union of  $k$  vertex disjoint copies of  $H_0$ . When  $H_0$

is a single edge  $E_r$ , a multiple copy is usually called a *matching*. The Ramsey number of multiple copies of graphs have been thoroughly studied, the first such results were perhaps [3] and [5] - both in 1975. The Ramsey number of a hypergraph matching is known exactly. The most general case is due to Alon, Frankl and Lovász (1986, [2]):

**Theorem 3.** *Assume that  $N = kr + (t-1)(k-1)$  and the edges of the complete  $r$ -uniform hypergraph  $K_N^r$  are colored with  $t$  colors. Then there is a monochromatic matching of size  $k$ .*

One can easily see that Theorem 3 is sharp. Partition a set  $S$  of  $N-1$  elements into  $t$  parts,  $A_1, A_2, \dots, A_t$  so that  $|A_i| = k-1$  for  $1 \leq i < t$ . For  $T \subset S$ ,  $|T| = r$ , color  $T$  with the smallest  $i$  such that  $T \cap A_i \neq \emptyset$ . Therefore - using the notation of Ramsey theory - it follows that

$$R_t(kE_r) = R(kE_r, kE_r, \dots, kE_r) = kr + (t-1)(k-1),$$

where the dots stand for  $t$  arguments. It is worth noting that Theorem 3 was conjectured by Erdős in 1973, [6] (rediscovered in [11]). Its special cases include earlier results:  $r = 2$  (1975, Cockayne - Lorrimer, [5]),  $k = 2$  (this is another form of Kneser's conjecture proved in 1978 by Lovász and Bárány) and  $t = 2$  (Alon and Frankl [1] and Gyárfás [11]).

Next we state and prove the Ramsey-type form of our main result, it determines the exact value of the Ramsey number of a diamond-matching.

**Theorem 4.** *For every  $k \geq 1, r \geq 2$   $R(kD_r, kD_r) = k(2r-1) - 1$ .*

*Proof.* To see that the stated value is a lower bound, consider a coloring of the edges of  $K_{k(2r-1)-2}^r$  where all edges intersecting a fixed  $(k-1)$ -element subset are red and all other edges are blue.

To see that  $m = k(2r-1) - 1$  is an upper bound for  $R(kD_r, kD_r)$ , consider a 2-coloring  $c$  of  $E(K_m^r)$ . For every set  $T \subset V(K_m^r)$  with  $|T| = 2r-2$  consider the 2-coloring  $c^*$  on the  $(r-2)$ -element subsets of  $T$  by coloring  $S \subset T$ ,  $|S| = r-2$ , with  $c(T \setminus S)$ . By Theorem 3,  $R(2E_{r-2}, 2E_{r-2}) = 2(r-2) + 1 = 2r-3$ , so there are two disjoint sets colored with the same color under  $c^*$  and this implies that there is a monochromatic  $D_r \subset T$  under  $c$ . The color of this monochromatic  $D_r$  can be used to color  $T$ . Applying Theorem 3 again to this coloring,  $R(kE_{2r-2}, kE_{2r-2}) = k(2r-2) + k-1 = k(2r-1) - 1$ , so we get that there is a monochromatic  $k$ -matching and this gives a monochromatic  $kD_r$ , finishing the proof.  $\square$

In fact, the proof method of Theorem 4 can be copied to determine the 3-colored Ramsey number of the diamond-matching as well.

**Theorem 5.** *For every  $k \geq 1, r \geq 2$   $R(kD_r, kD_r, kD_r) = 2kr - 2$ .*

*Proof.* To see that the claimed value is a lower bound, partition a  $(2kr-3)$ -element set  $V$  into  $A_1, A_2, A_3$  with  $|A_1| = |A_2| = k-1, |A_3| = k(2r-2) - 1$ . Let  $S \subset V$ ,  $|S| = r$ , and color  $S$  with the minimum  $i$  for which  $S \cap A_i \neq \emptyset$ .

To prove the upper bound, let  $c$  be a 3-coloring of the edges of  $K_m^r$  with  $m = 2kr - 2$ .

For every set  $T \subset V(K_m^r)$  with  $|T| = 2r - 2$  consider the 3-coloring  $c^*$  on the  $(r - 2)$ -element subsets of  $T$  by coloring  $S \subset T$ ,  $|S| = r - 2$ , with  $c(T \setminus S)$ . By Theorem 3,  $R(2E_{r-2}, 2E_{r-2}, 2E_{r-2}) = 2(r - 2) + 2 = 2r - 2$  so there are two disjoint sets colored with the same color under  $c^*$ . This implies that there is a monochromatic  $D_r \subset T$  under  $c$ . The color of this monochromatic  $D_r$  can be used to color  $T$ . Applying Theorem 3 again to this coloring,  $R(kE_{2r-2}, kE_{2r-2}, kE_{2r-2}) = k(2r - 2) + 2(k - 1) = 2kr - 2$ , so we get that there is a monochromatic  $k$ -matching and this gives a monochromatic  $kD_r$ , finishing the proof.  $\square$

For our purposes we need a proof of Theorem 4 that carries over to almost complete hypergraphs. We use a compression principle that occurred first perhaps in [5] and in [3]. For example, a red and a blue triangle with a common vertex was called a bow tie (see [10]), it drives the inductive argument of [3] to prove that  $R(kK_3, kK_3) = 5k$  (for  $k \geq 2$ ). Similar compression - a red and a blue  $E_r$  intersecting in  $r - 1$  elements - makes the proof of Theorem 3 easy when  $t = 2$  (it seems that for  $t > 2$  the Borsuk - Ulam theorem is essential). In fact, the first author suggested the case  $t = 2, k = r$  as a problem for the 2007 USA Mathematical Olympiad (Problem 3 on the first day). For our case, the diamond matching, the compressed structure is a red and a blue diamond within  $2r - 1$  vertices. We note here that for  $r = 3$  this structure played a role also in [16], (it was called a diadem there).

## 1.2 Almost complete graphs, selection lemma

Throughout this section  $r \geq 2$  is a fixed integer,  $0 < \epsilon < 1$  is arbitrary small but fixed,  $n$  approaches infinity (thus arbitrarily large). Greek letters  $\delta, \rho$ , etc. will be used to denote numbers that tend to zero when  $\epsilon$  tends to zero ( $r$  is fixed). Hypergraph  $\mathcal{H}$  is a  $(1 - \epsilon)$ -complete  $r$ -uniform hypergraph on  $n$  vertices, i.e. is obtained from  $K_n^{(r)}$  by deleting at most  $\epsilon \binom{n}{r}$  edges. For easier computation we shall assume that  $|E(\mathcal{H})| \geq (1 - \epsilon)n^r/r!$ .

Different technical lemmas have been used earlier to handle almost complete graphs and 3-uniform hypergraphs (see [13], [16]). Here we use the concept of  $\delta$ -bounded selection, a tool introduced and used in [12] and in [15]. It is convenient for almost complete hypergraphs when one needs to show that there exists at least one edge at a prescribed spot or there are many edges where they need to be.

For  $0 < \delta < 1$  fixed, we say that a sequence  $L \subset V(\mathcal{H})$  of  $k$  distinct vertices was obtained by a  $\delta$ -bounded selection if its elements are chosen in  $k$  consecutive steps so that in each step there are at most  $\delta n$  forbidden vertices that cannot be included as the next element. For simplicity, sometimes we will call shortly the sequence *itself* a  $\delta$ -bounded selection. Observe that a  $\delta$ -bounded selection  $L$  is also a  $\delta'$ -bounded selection for any  $\delta' > \delta$ .

In the subsequent applications when specifying a  $\delta$ -bounded selection of  $k$  vertices in an  $(1 - \epsilon)$ -dense hypergraph, we would like to guarantee that

for every subset  $S$  of the selected vertices such that  $0 \leq |S| \leq r$ , at least  $(1 - \rho)n^{r-|S|}/(r - |S|)!$  edges of  $\mathcal{H}$  contain  $S$  (where  $\rho$  tends to zero with  $\epsilon$ ,  $r, k$  are fixed). Notice that - if  $1 - \rho > 0$  and  $k \geq r$  - we require in particular that the selected vertices form a complete  $r$ -uniform subhypergraph. Observe that for  $k = 0$  we need that  $\mathcal{H}$  has at least  $(1 - \rho)n^r/r!$  edges, which is obvious with  $\rho = \epsilon$ . For larger  $k$  our argument will be based on the following recurrence lemma (from [12]).

**Lemma 6.** *Let  $S_0 \subset V(\mathcal{H})$  be contained in at least  $(1 - \rho_0) \frac{n^{r-|S_0|}}{(r-|S_0|)!}$  edges of  $\mathcal{H}$ . If  $|S_0| < r$  and  $\rho = \sqrt{\rho_0}$ , then there exists  $F_0 \subset V(\mathcal{H})$ ,  $|F_0| \leq \rho n$ , such that for every  $x \in V(\mathcal{H}) \setminus (S_0 \cup F_0)$  at least  $(1 - \rho) \frac{n^{r-|S|}}{(r-|S|)!}$  edges of  $\mathcal{H}$  contain  $S = S_0 \cup \{x\}$ .*

*Proof.* Let  $|S_0| = i < r$ . By the assumption, there are  $\beta \leq \rho_0 n^{r-i}/(r-i)!$  distinct  $(r-i)$ -element “bad” subsets  $B \subseteq V(\mathcal{H}) \setminus S_0$  with  $S_0 \cup B \notin E(\mathcal{H})$ . Let  $F_0 \subseteq V(\mathcal{H}) \setminus S_0$  be the set of all vertices contained in more than  $\rho n^{r-i-1}/(r-i-1)!$  distinct  $(r-i)$ -element bad sets. We clearly have  $\beta \geq |F_0| \rho n^{r-i-1}/(r-i)!$ .

By comparing these two bounds on  $\beta$ , we obtain that  $|F_0| \leq \frac{\rho_0}{\rho} n = \rho n$  and the lemma follows.  $\square$

We shall use Lemma 6 to prove the following selection Lemma (its special case  $k = r$  is from [12]).

**Lemma 7.** *Assume that  $\mathcal{H}$  is a  $(1 - \epsilon)$ -complete  $r$ -uniform hypergraph ( $r \geq 2$ ) and set  $\rho = \epsilon^{2^{-r}}$ ,  $\delta = 2^k \rho$ . There are forbidden sets such that for every  $L \subset V(\mathcal{H})$  of  $k$  vertices that was obtained by a  $\delta$ -bounded selection (with respect to the forbidden sets), the following holds: for every  $S \subseteq L$  such that  $0 \leq |S| \leq r$ , at least  $(1 - \rho) \frac{n^{r-|S|}}{(r-|S|)!}$  edges of  $\mathcal{H}$  contain  $S$ .*

*Proof.* We iterate Lemma 6 as we select  $x_1, x_2, \dots, x_k$  in  $k$  steps, in each step we consider all subsets of size less than  $r$  to extend with a new vertex. At step  $i$  we ensure that for every  $\delta_i$ -bounded selection  $L$  of  $i$  vertices the following holds: for every  $S \subseteq L$  such that  $0 \leq |S| \leq r$ , at least  $(1 - \epsilon^{2^{-|S|}}) \frac{n^{r-|S|}}{(r-|S|)!}$  edges of  $\mathcal{H}$  contain  $S$ . For  $k = 0$   $\delta_0 = \epsilon$  obviously works. Assume this is true with  $\delta_i$  for step  $i$ ,  $0 \leq i < k$ . At step  $i + 1$  to ensure that  $x_{i+1}$  can be selected, we use Lemma 6 for all  $S_0 \subseteq \{x_1, \dots, x_i\}$  such that  $|S_0| < r$ . By Lemma 6, for each  $j$ -element  $S_0$  there exists a forbidden set  $F_0$  for  $x_{i+1}$  with  $|F_0| \leq \epsilon^{2^{-(j+1)}} n$  such that  $S = S_0 \cup \{x_{i+1}\}$  will be in at least  $(1 - \epsilon^{2^{-|S|}}) \frac{n^{r-|S|}}{(r-|S|)!}$  edges of  $\mathcal{H}$ . There are  $\sum_{j < r} \binom{i}{j} < 2^i$  choices for  $S_0$  and each  $j$ -element  $S_0$  forbids  $\epsilon^{2^{-(j+1)}} n$  choices of  $x_{i+1}$ . Thus altogether the set of forbidden vertices for  $x_{i+1}$  is less than  $2^i \epsilon^{2^{-r}} n$ , so  $\delta_{i+1} = 2^i \epsilon^{2^{-r}}$  is a good choice for step  $i + 1$ . On the other hand,  $\rho = \epsilon^{2^{-r}}$  is a good choice for every step since we iterate the square root operation of Lemma 6 at most  $r$  times (to extend sets of size less than  $r$ ).

Since

$$\delta_{i+1} = 2^i \epsilon^{2^{-r}} \leq 2^k \epsilon^{2^{-r}} = 2^k \rho = \delta,$$

the statement of the lemma holds with  $\delta = 2^k \epsilon^{2^{-r}} = 2^k \rho$ .  $\square$

## 2 Proof of Theorem 1

The following proposition is from [12].

**Proposition 8.** *Assume  $\mathcal{H}$  is an arbitrary hypergraph and  $0 < s < 1/3$ . Then either there is a connected component  $\mathcal{H}'$  of  $\mathcal{H}$  with at least  $(1-s)n$  vertices or the connected components of  $\mathcal{H}$  can be partitioned into two groups so that each group contains more than  $sn$  vertices.*

*Proof.* Mark the connected components of  $\mathcal{H}$  until the union of them has at most  $sn$  vertices. If one unmarked component remains, it can be  $\mathcal{H}'$ . Otherwise, we form two groups from the unmarked components. The larger group has order at least  $(n - sn)/2 > sn$ , and the smaller one together with the marked components have a union containing more than  $sn$  vertices as well.  $\square$

To prove Theorem 1, consider a 2-coloring  $c$  of an  $(1-\epsilon)$ -complete  $r$ -uniform hypergraph  $\mathcal{H}$ . Let  $\mathcal{H}_R, \mathcal{H}_B$  denote the hypergraphs determined by the red and blue edges of  $\mathcal{H}$ . Initially we select  $\delta$  to satisfy Lemma 7, i.e.  $\delta \leq 2^k \rho = 2^k \epsilon^{2^{-r}}$  and also  $\delta < \frac{1}{2r-1} < \frac{1}{3}$ . During the proof we shall use  $\delta$ -bounded selections of  $k < 4r$  vertices.

We start by applying Proposition 8 with  $s = \delta$  to  $\mathcal{H}_R$  and to  $\mathcal{H}_B$ .

If the first possibility holds to one of them, say to  $\mathcal{H}_R$ , we find a subhypergraph  $\mathcal{H}_1$  with at least  $(1-\delta)n$  vertices that is connected in red. Now apply Proposition 8 again to the hypergraph determined by the blue edges of  $\mathcal{H}_1$ . If the first possibility holds then we have a subhypergraph  $\mathcal{H}_2$  of  $\mathcal{H}_1$  with at least  $(1-2\delta)n$  vertices that is connected in blue and also part of the connected red hypergraph  $\mathcal{H}_1$ . Since we loose at most  $2\delta n = o(n)$  vertices, for convenience, we still use the notation  $\mathcal{H}$  for  $\mathcal{H}_i$  (case A). To comply with the notation of cases B1, B2 below, set  $Y = V$  in case A.

Assume that the first possibility does not hold for at least one of the steps above (case B). We may assume that it does not hold in the first step. We look at two subcases. Apply again Proposition 8 to  $\mathcal{H}_R$  but with  $s = \frac{1}{2r-1}$ .

If the first possibility holds, the vertex set of  $\mathcal{H}$  is partitioned into  $X$  and  $Y$  so that  $|X| < \frac{n}{2r-1}$  and  $Y$  is a connected component of  $\mathcal{H}_R$  (subcase B1). Notice that  $\delta n < |X|$  is also true since we are in case B.

If the second possibility holds then the components of  $\mathcal{H}_R$  can be partitioned into  $X$  and  $Y$  such that  $\frac{n}{2r-1} \leq |X| \leq |Y|$  (subcase B2).

Notice that (in both subcases) all edges of  $\mathcal{H}$  meeting both  $X$  and  $Y$  are blue. For the rest of the proof we assume that  $x_1, x_2$  are the first two vertices of a  $\delta$ -bounded selection process on  $\mathcal{H}$ . Moreover, let  $\mathcal{H}^*$  be the  $(r-2)$ -uniform hypergraph induced on  $Z = V \setminus \{x_1, x_2\}$  by  $\mathcal{H}$  together with the induced 2-coloring  $c(x_1, x_2)$ . Notice that  $\mathcal{H}^*$  is an almost complete  $(r-2)$ -uniform hypergraph with parameter  $\epsilon^* = \rho = \epsilon^{2^{-r}}$ . Using  $\epsilon^*$  in the role of  $\epsilon$ , we can define  $\delta^*, \rho^*$  as defined in Lemma 7. The key in our proof is the following compression lemma.

**Lemma 9.** Assume that  $\mathcal{H}$  is a 2-colored  $(1-\epsilon)$ -complete  $r$ -uniform hypergraph on  $n$  vertices. Suppose that the pair  $x_1, x_2 \in V(\mathcal{H})$  is in at least  $\mu \binom{n}{r-2}$  edges in both colors, where  $\mu = 1 - (1 - \rho - \rho^*)^{r-2}$ . Then one can find a diamond in both colors within  $2r - 1$  vertices.

*Proof.* Combining the at most  $(\delta + \delta^*)n \leq 2\delta^*$  forbidden sets of  $\mathcal{H}$  and  $\mathcal{H}^*$  we have that every  $2\delta^*$ -bounded selection  $x_1, x_2, y_1, y_2, \dots, y_k$  of vertices of  $\mathcal{H}$  (where  $k = 4(r - 2)$ ) satisfies the property ensured by Lemma 7 simultaneously i.e.  $x_1, x_2, y_1, y_2, \dots, y_k$  is on  $\mathcal{H}$  and  $y_1, y_2, \dots, y_k$  is on  $\mathcal{H}^*$ . This ensures, in particular, that the  $r$ -uniform subhypergraph of  $\mathcal{H}$  spanned by  $x_1, x_2, y_1, y_2, \dots, y_k$  and the  $(r - 2)$ -uniform subhypergraph of  $\mathcal{H}^*$  spanned by  $y_1, y_2, \dots, y_k$  are complete subhypergraphs.

Fix an edge  $e \in \mathcal{H}^*$  with vertex set  $\{y_1, \dots, y_{r-2}\}$ , say  $e$  is red under  $c(x_1, x_2)$ . Consider the subhypergraph  $\mathcal{F}$  of  $\mathcal{H}^*$  with edges that can be obtained as the next  $r - 2$  vertices,  $y_{r-1}, \dots, y_{2r-4}$  in the selection. The choice of  $\mu$  and the lower bound on the number of blue edges ensures that at least one edge  $f \in \mathcal{F}$  is blue (under  $c(x_1, x_2)$ ):

$$|\mathcal{F}| > \frac{(1 - \rho - \rho^*)^{r-2} n^{r-2}}{(r - 2)!} = \frac{(1 - \mu) n^{r-2}}{(r - 2)!} > (1 - \mu) \binom{n}{r - 2} \geq |E(\mathcal{H}_R^*)|.$$

Consider the complete  $r - 2$ -uniform hypergraph  $\mathcal{F} \subset \mathcal{H}^*$  spanned by the vertex set of  $e \cup f$ . Among all pairs of edges of  $\mathcal{F}$  with distinct colors (there are pairs like that:  $e, f$ ) select a pair  $R_1, B_1$  with largest intersection. Clearly,  $|R_1 \cap B_1| = r - 3$ .

Repeat the previous procedure by fixing an edge with vertices  $y_{2r-3}, \dots, y_{3r-2}$  in  $\mathcal{H}^*$  then find an edge of the other color. By taking a pair with largest intersection again, we have another red-blue pair of edges  $R_2, B_2$  such that  $|R_2 \cap B_2| = r - 3$ . Notice that  $R_1 \cup B_1$  and  $R_2 \cup B_2$  are vertex disjoint. Define  $r_1 = R_1 \setminus B_1$ ,  $r_2 = R_2 \setminus B_2$ ,  $b_1 = B_1 \setminus R_1$ ,  $b_2 = B_2 \setminus R_2$ .

Notice that the (complete) subhypergraph of  $\mathcal{H}$  spanned by  $\{x_1, x_2\} \cup R_1 \cup R_2 \cup B_1 \cup B_2$  has  $2r$  vertices and contains  $D_r$  in both colors. To finish the proof, we need to find a vertex whose deletion keeps a copy of  $D_r$  in both colors.

Consider the  $r$ -element set  $U_1$  that is the union of  $B_2$ , one vertex of  $R_1 \cap B_1$  and the vertex  $r_1$ . (In case of  $r = 3$   $R_1 \cap B_1$  is empty - then we can select  $x_1$  as the third vertex and  $r_2$  or  $b_1$  can be removed, the argument ends here.) If  $U_1$  is red (under  $c$ ) then the vertex  $r_2$  can be removed and we get both red and blue diamonds within  $2r - 1$  vertices. Thus we may assume that  $U_1$  is blue. Similar argument gives that  $U_2$ , defined as the union of  $R_1$ , one vertex of  $R_2 \cap B_2$  and the vertex  $b_2$  is red. Likewise,  $U_3$  defined as the union of  $B_1$ , one vertex of  $R_2 \cap B_2$  and the vertex  $r_2$  is blue, finally  $U_4$ , defined as the union of  $R_2$ , one vertex of  $R_1 \cap B_1$  and the vertex  $b_1$  is red. Now  $U_1 \cup U_3$  and  $U_2 \cup U_4$  are the required diamonds (in fact they are within  $2r - 2$  vertices).  $\square$

Continuing the proof of Theorem 1, we try to cover as many vertices of  $Y$  as we can with pairwise disjoint sets  $S_i$ ,  $i = 1, 2, \dots, m$  that contain diamonds of both colors and  $|S_i| = 2r - 1$ . Set  $S = \cup_{i=1}^m S_i$ ,  $T = Y \setminus S$ . The hypergraphs



induced by  $\mathcal{H}$  on  $S, T$  are denoted by  $\mathcal{S}, \mathcal{T}$ . Since we can not find a new  $S_i \subset T$  with Lemma 9, there is a color for every pair  $x_1, x_2 \in T$  such that there are more than  $(1 - \mu) \binom{|T|}{r-2}$  edges in that color in the coloring  $c(x_1, x_2)$ . Assign that color to the pair  $x_1, x_2$ , to get a 2-coloring  $C$  on the graph  $G$  whose edges are the pairs available as the first two vertices on a  $\delta$ -bounded selection on  $\mathcal{T}$ . Notice that  $G$  is an  $(1 - 2\delta)$ -complete graph.

We claim that  $\mathcal{T}$  has an almost perfect monochromatic diamond matching  $\mathcal{M}$  (i.e.  $V(\mathcal{T})$  can be partitioned into vertex disjoint diamonds all of the same color, apart from  $o(n)$  vertices.) First we show that almost all edges of  $G$  are colored with the same color (under  $C$ ). Indeed, otherwise - using that  $G$  is almost complete - we could easily find a red edge  $uv$  and a blue edge  $vw$  of  $G$ . Define a coloring  $c^*$  by restricting the colorings  $c(u, v), c(v, w)$  to the hypergraph  $\mathcal{T}^*$  whose edges are the  $(r - 2)$ -element subsets  $e \subset T$  for which  $e \cup \{u, v\}$  and  $e \cup \{v, w\}$  are both in  $\mathcal{H}$ . Observe that  $c^*$  colors every edge of an  $(1 - 2\mu - 2\epsilon^*)$ -complete  $(r - 2)$ -uniform hypergraph with both red and blue colors. Then one can make a  $\delta$ -selection  $u, v, w, y_1, \dots, y_{2r-4}$  such that  $y_1, \dots, y_{2r-4}$  spans a  $K_{r-2}^{2(r-2)}$  with all edges colored in both colors. In particular, we have a red and a blue  $D_r$  within  $2r - 1$  vertices of  $T$ , contradicting the choice of  $m$ . This proves the claim.

In case A both colors define a connected hypergraph so the diamonds in the color of  $\mathcal{M}$  together with the diamonds of the appropriate color from the  $S_i$ -s provide the monochromatic connected diamond matching, covering approximately a portion of  $\frac{2r-2}{2r-1}$  of the vertex set of  $\mathcal{H}$ .

In case B2 it is easy to cover the required portion of vertices by blue diamonds since all edges meeting both  $X$  and  $Y$  are blue and  $\frac{n}{2r-1} \leq |X| \leq |Y|$  (connectivity of the blue hypergraph is obvious). In fact, one can cover approximately  $\frac{(2r-2)n}{2r-1}$  vertices with vertex disjoint blue diamonds using only diamonds of type  $(1, 2r - 3)$  and  $(2r - 3, 1)$  where type  $(a, b)$  means a diamond intersecting  $X, Y$  in  $a$  and  $b$  vertices, respectively with its center vertices in  $X, Y$ . The reason is that flipping one blue diamond in a diamond matching from type  $(1, 2r - 3)$  to type  $(2r - 3, 1)$  changes the cover ratio of  $Y$  and  $X$  by at most a quantity that tends to zero if  $n$  tends to infinity ( $r$  is fixed). The details are left to the reader. This argument extends to case B1 as well, if  $m \geq \frac{n}{2r-1} - |X|$ : in addition to the blue diamonds meeting both  $X$  and  $Y$  we can use the blue diamonds of  $S_i$ . Thus we may assume that  $m < \frac{n}{2r-1} - |X|$ .

If  $\mathcal{M}$  is red then the diamonds of  $\mathcal{M}$  together with the red diamonds of the  $S_i$ -s cover all but  $m + |X| < \frac{n}{2r-1} - |X| + |X| = \frac{n}{2r-1}$  vertices, finishing the proof. If  $\mathcal{M}$  is blue we can do the same in blue - here we gain since all diamonds meeting  $X$  and vertices uncovered by the blue diamonds of  $S_i$  are giving extra to the covered area. This finishes the proof of Theorem 1.  $\square$

### 3 From connected diamond matchings to loose cycles

For the sake of completeness here we sketch how the method of [16] with minor modifications (that are needed since the uniformity is  $r$  instead of 3) can be used to transform our asymptotic result on monochromatic connected diamond matchings (Theorem 1) to our asymptotic result on monochromatic loose cycles (Theorem 2). The missing details can be found in [16].

The main tool is the hypergraph version of the Regularity Lemma of Szemerédi [21]. We shall assume throughout the rest of the paper that  $n$  is sufficiently large and  $r$  is fixed.

There are several generalizations of the Regularity Lemma for hypergraphs due to various authors ([4], [8], for an extensive survey see [18], new developments are in [9], [20] and [22]). Following [16], the simplest one, due to Chung [4] can be used. To state it, one needs to define the notion of  $\varepsilon$ -regularity. Let  $\varepsilon > 0$  and let  $V_1, V_2, \dots, V_r$  be disjoint vertex sets of order  $m$ , and let  $\mathcal{H}$  be an  $r$ -uniform hypergraph such that every edge of  $\mathcal{H}$  contains exactly one vertex from each  $V_i$  for  $i = 1, 2, \dots, r$ . The density of  $\mathcal{H}$  is  $d_{\mathcal{H}} = \frac{|E(\mathcal{H})|}{m^r}$ . The  $r$ -tuple  $\{V_1, V_2, \dots, V_r\}$  is called an  $(\varepsilon, \mathcal{H})$ -regular  $r$ -tuple of density  $d_{\mathcal{H}}$  if for every choice of  $X_i \subset V_i$ ,  $|X_i| > \varepsilon|V_i|$ ,  $i = 1, 2, \dots, r$  we have

$$\left| \frac{|E(\mathcal{H}[X_1, \dots, X_r])|}{|X_1| \dots |X_r|} - d_{\mathcal{H}} \right| < \varepsilon.$$

Here we denote by  $\mathcal{H}[X_1, \dots, X_r]$  the subhypergraph of  $\mathcal{H}$  induced by the vertex set  $X_1 \cup \dots \cup X_r$ . Similarly as in [16] for  $r = 3$ , we need a 2-color version of the Hypergraph Regularity Lemma from [4] for general  $r$ .

**Lemma 10 (2-color Weak Hypergraph Regularity Lemma).** *For every positive  $\varepsilon$  and positive integers  $t, r$  there are positive integers  $M$  and  $n_0$  such that for  $n \geq n_0$  the following holds. For all  $r$ -uniform hypergraphs  $\mathcal{H}_1, \mathcal{H}_2$  with  $V(\mathcal{H}_1) = V(\mathcal{H}_2)$ ,  $|V| = n$ , there is a partition of  $V$  into  $l + 1$  classes (clusters)*

$$V = V_0 + V_1 + V_2 + \dots + V_l$$

such that

- $t \leq l \leq M$
- $|V_1| = |V_2| = \dots = |V_l|$
- $|V_0| < \varepsilon n$
- *apart from at most  $\varepsilon \binom{l}{r}$  exceptional  $r$ -tuples, the  $r$ -tuples  $\{V_{i_1}, V_{i_2}, \dots, V_{i_r}\}$  are  $(\varepsilon, \mathcal{H}_s)$ -regular for  $s = 1, 2$ .*

Consider a 2-edge coloring  $(\mathcal{H}_1, \mathcal{H}_2)$  of the  $r$ -uniform complete hypergraph  $K_N^{(r)}$ , where  $N \sim \frac{(2r-1)n}{2r-2}$ , i.e.  $\mathcal{H}_1$  is the subhypergraph induced by the first

color (say red) and  $\mathcal{H}_2$  is the subhypergraph induced by the second color (say blue).

We apply the above 2-color Weak Hypergraph Regularity Lemma with  $t = r$  and with a small enough  $\varepsilon$  to obtain a partition of  $V(K_N^{(r)}) = V = \cup_{0 \leq i \leq l} V_i$ , where  $|V_i| = \frac{N - |V_0|}{l} = m, 1 \leq i \leq l$ . We define the following *reduced hypergraph*  $\mathcal{H}^R$ : The vertices of  $\mathcal{H}^R$  are  $p_1, \dots, p_l$ , and we have an  $r$ -edge on vertices  $p_{i_1}, p_{i_2}, \dots, p_{i_r}$  if the  $r$ -tuple  $\{V_{i_1}, V_{i_2}, \dots, V_{i_r}\}$  is  $(\varepsilon, \mathcal{H}_s)$ -regular for  $s = 1, 2$ . Thus we have a one-to-one correspondence  $f : p_i \rightarrow V_i$  between the vertices of  $\mathcal{H}^R$  and the clusters of the partition. Then,

$$|E(\mathcal{H}^R)| \geq (1 - \varepsilon) \binom{l}{r},$$

and thus  $\mathcal{H}^R$  is a  $(1 - \varepsilon)$ -complete  $r$ -uniform hypergraph on  $l$  vertices. Define a 2-edge coloring  $(\mathcal{H}_1^R, \mathcal{H}_2^R)$  of  $\mathcal{H}^R$  with the majority color, i.e. the  $r$ -tuple  $\{p_{i_1}, p_{i_2}, \dots, p_{i_r}\} \in E(\mathcal{H}_s^R)$  if  $s$  is the more frequent color in the  $r$ -tuple  $\{V_{i_1}, V_{i_2}, \dots, V_{i_r}\} \in E(\mathcal{H}_s)$ . Note then that the density of this color is  $\geq 1/2$  in this  $r$ -tuple. Finally we consider the multicolored shadow graph  $\Gamma(\mathcal{H}^R)$ . The vertices are  $V(\mathcal{H}^R) = \{p_1, \dots, p_l\}$  and we join vertices  $x$  and  $y$  by an edge of color  $s, s = 1, 2$  if  $x$  and  $y$  are contained in an edge of  $\mathcal{H}^R$  that is colored with color  $s$ .

Applying Theorem 1 to the 2-colored almost complete reduced graph  $\mathcal{H}^R$  we get a monochromatic (say red) connected diamond matching  $D_r^1, \dots, D_r^k$  with  $k(2r - 2) \sim \frac{(2r-2)l}{2r-1}$ , i.e.  $k \sim l/(2r - 1)$ . Let  $\mathcal{L}$  be the red component of  $\mathcal{H}^R$  that contains these diamonds.

Applying the method of [16] to find the red  $\mathcal{C}_n^r$  we do the following. We first trace a “route” in  $\mathcal{L}$ , that visits all the diamonds  $D_r^1, \dots, D_r^k$ . Then we choose a collection of short loose paths (of length three or six) in the red subhypergraph  $\mathcal{H}_1$ , that link together to form a short loose cycle, following the chosen route. Finally, to obtain the red loose cycle  $\mathcal{C}_n^r$  we “blow-up”  $k \sim l/(2r - 1)$  short paths (of length three) corresponding to diamonds by long paths (each of length  $\sim (2r - 2)m \sim (2r - 2)N/l \sim (2r - 1)n/l$ ). More precisely, for each diamond  $D_r^i$  with middle clusters  $V_1^i$  and  $V_2^i$ , we replace the short path that starts with in  $V_1^i$  and ends in  $V_2^i$  by a long path with the same end-vertices, that uses almost all the vertices in  $D_r^i$ . Note that these long paths are mutually vertex disjoint since all diamonds  $D_r^i$  are vertex disjoint. Therefore, to obtain our cycle, we just need to make sure that the short paths do not intersect and they do not interfere with the long paths.

This plan can be achieved via the same sequence of lemmas as in [16]. To demonstrate what kind of minor modifications are needed in these lemmas for  $r$ -uniform hypergraphs, we present the modified version of perhaps the most important lemma, Lemma 5.3 in [16], that shows how to find the short connecting loose paths of length three. First we need the following definition.

Let  $\{V_{i_1}, \dots, V_{i_r}\}$  be an  $(\varepsilon, \mathcal{H}_1)$ -regular  $r$ -tuple with density  $d > 2\varepsilon$ , and for  $j = 1, \dots, r$  let  $U_{i_j} \subset V_{i_j}$  be arbitrary subsets. We say that a vertex  $x \in V_{i_1}$  is *good for the  $r$ -tuple*  $\{U_{i_1}, \dots, U_{i_r}\}$  if for every  $j = 2, \dots, r$  there

are at least  $d|U_{i_j}|/2$  vertices  $y \in U_{i_j}$ , such that for each such  $y$ , there are at least  $d|U_{i_2}|/2$  vertices  $z_1 \in U_{i_2}$ , such that for each such  $z_1$ , there are at least  $d|U_{i_3}|/2$  vertices  $z_2 \in U_{i_3}$ , etc. we go through the sets  $U_{i_{j'}}, j' = 2, \dots, r, j' \neq j$  with this process, finally there are at least  $d|U_{i_r}|/2$  vertices  $z_{r-2} \in U_{i_r}$ , such that  $\{x, y, z_1, \dots, z_{r-2}\} \in E(\mathcal{H}_1)$ . Thus note that for  $x \in V_{i_1}$ , the property of being good for  $\{U_{i_1}, \dots, U_{i_r}\}$  is independent of the choice of  $U_{i_1}$ . The set of vertices in  $V_{i_1} \cup \dots \cup V_{i_r}$  that are good for  $\{V_{i_1}, \dots, V_{i_r}\}$  will simply be called good.

We modify Lemma 5.3 of [16] in the following way for  $r$ -uniform hypergraphs.

**Lemma 11.** *Let  $\{V_{i_1}, \dots, V_{i_r}\}$  be an  $(\varepsilon, \mathcal{H}_1)$ -regular  $r$ -tuple with density  $d > 2\varepsilon$ . Then for every pair of good vertices  $x \in V_{i_1}$  and  $y \in V_{i_2}$ , and for every set  $B \subset V_{i_1} \cup \dots \cup V_{i_r} \setminus \{x, y\}$  that contains all non-good vertices and satisfies  $|B \cap V_{i_j}| < (d/2 - \varepsilon)m$  for  $j = 2, \dots, r$ , there is a path of length three in  $\mathcal{H}_1$  joining  $x$  to  $y$  that is disjoint from  $B$  (and hence contains only good vertices). Moreover the path can be chosen so that one vertex of degree two in the path is in  $V_{i_1}$ , and the other is in  $V_{i_2}$ .*

*Proof.* Since  $x$  is good, there exists a set  $U_x \subset V_{i_2}$ ,  $|U_x| \geq dm/2$  (using  $j = 2$  from the definition), such that for each  $w \in U_x$ , there are at least  $dm/2$  vertices  $z_1 \in V_{i_3}$ , such that for each such  $z_1$ , there are at least  $dm/2$  vertices  $z_2 \in V_{i_4}$ , etc., finally there are at least  $dm/2$  vertices  $z_{r-2} \in V_{i_r}$ , such that  $\{x, w, z_1, \dots, z_{r-2}\} \in E(\mathcal{H}_1)$ . Similarly, since  $y$  is good, there exists a set  $U_y \subset V_{i_1}$ ,  $|U_y| \geq dm/2$  (using  $j = 1$  from the definition), such that for each  $v \in U_y$ , there are at least  $dm/2$  vertices  $z_1 \in V_{i_3}$ , such that for each such  $z_1$ , there are at least  $dm/2$  vertices  $z_2 \in V_{i_4}$ , etc., finally there are at least  $dm/2$  vertices  $z_{r-2} \in V_{i_r}$ , such that  $\{y, v, z_1, \dots, z_{r-2}\} \in E(\mathcal{H}_1)$ . Writing  $b = (d/2 - \varepsilon)$ , we have

$$|U_x \setminus B|, |U_y \setminus B| > (d/2 - b)m = \varepsilon m.$$

Therefore, since  $\{V_{i_1}, \dots, V_{i_r}\}$  is an  $(\varepsilon, \mathcal{H}_1)$ -regular  $r$ -tuple with density  $d$ , we know that

$$|E(\mathcal{H}[U_x \setminus B, U_y \setminus B, V_{i_3} \setminus B, \dots, V_{i_r} \setminus B])| \geq (d - \varepsilon)|U_x \setminus B||U_y \setminus B| \prod_{j=3}^r |V_{i_j} \setminus B|.$$

We may therefore choose distinct vertices  $w \in U_x \setminus \{y\}$ ,  $v \in U_y \setminus \{x\}$ ,  $z_1^1, z_1^2, z_1^3 \in V_{i_3}$ ,  $z_2^1, z_2^2, z_2^3 \in V_{i_4}$ ,  $\dots$ ,  $z_{r-2}^1, z_{r-2}^2, z_{r-2}^3 \in V_{i_r}$  such that

$$\{x, w, z_1^1, \dots, z_{r-2}^1\}, \{y, v, z_1^2, \dots, z_{r-2}^2\}, \{v, w, z_1^3, \dots, z_{r-2}^3\} \in E(\mathcal{H}_1).$$

This gives us the required loose path of length three joining  $x$  to  $y$

$$x, z_1^1, \dots, z_{r-2}^1, w, z_1^3, \dots, z_{r-2}^3, v, z_1^2, \dots, z_{r-2}^2, y.$$

□

The other lemmas and the proof itself can be modified similarly, details can be found in [16]. This finishes the proof of Theorem 2.

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